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New Physics Prospects in Mixing and CP Violation at Belle II

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The Belle II experiment at the SuperKEKB electron-positron collider will provide a large sample of charm mesons in addition to its primary goal of B meson production. The large data sample and wide variety of accessible D meson decay modes in a clean experimental environment provide sensitivity to new physics via D meson mixing and CP violation measurements. This contribution briefly describes selected components of the upgrade from Belle to Belle II and KEKB to SuperKEKB, and some prospects for new physics searches in the areas of charm mixing and CP violation.

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1 Introduction

In addition to their primary mission of exploring CP violation and other properties of the B meson system, the B factory experiments Belle and BaBar have produced a wealth of measurements in the charm sector. This is in part due to the large cross section for charm production at these facilities. For example, at the nominal running energy of 10.58 GeV, the cross section for $e^+e^- \rightarrow c\bar{c}$ is actually larger than that of the nominal process, $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$. Cross sections for these two processes are 1.3 nb and 1.1 nb, respectively. Thus, over a decade of operation, Belle alone has collected $\approx 10^9$ charm events in over 1 ab^{-1} of integrated luminosity. This data set, combined with those taken by CLEOc, BaBar, LHCb, and others, are allowing increasingly precise probes for new physics in charm mixing and CP violation.

However, the nature of D meson mixing and CP violation are such that the effects are expected (and thus far observed) to be quite small. To make significant headway in future studies on these topics will require a substantial increase in statistics. Belle II and SuperKEKB are ongoing upgrades to the Belle detector and KEKB asymmetric e^+e^- collider, respectively, and will provide the necessary experimental precision to push these searches for new physics to the next level.

This contribution briefly introduces some D mixing and CP violation formalism, and describes measurements of these parameters that are particularly well suited for study at e^+e^- experiments. The current experimental status of selected measurements in these sectors is then described, and prospects for improved measurements with Belle II at SuperKEKB are presented.

2 D meson mixing and CP violation

As in other neutral meson systems, mixing occurs when the flavor and mass eigenstates are not identical. For the neutral D system, this is usually written as: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, where $D_{1,2}$ are the mass eigenstates and D^0, \bar{D}^0 are the flavor eigenstates. The parameters p and q must satisfy $|p|^2 + |q|^2 = 1$, and, if CP is conserved, $p = q$. In the D system, the mixing parameters are usually defined as $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/\Gamma$, where Δm and $\Delta\Gamma$ are the mass and decay width differences of the mass eigenstates, and Γ is the average decay width.

In the Standard Model, neutral D meson mixing is both CKM and GIM suppressed. For example, the parameter x is proportional to $(m_s^2 - m_d^2)/m_W^2$. Typical standard model expectations for both mixing parameters $|x|$ and $|y|$ are $\mathcal{O}(10^{-3})$ to $\mathcal{O}(10^{-2})$. The small expected values of the mixing parameters within the Standard Model make them an excellent place to search for new physics, as observation of large mixing would require non-Standard Model explanations.

CP violation is also expected to be quite small within the Standard Model, where

the CKM element responsible is $V_{cs} \sim \eta A^2 \lambda^4$, which is roughly $\mathcal{O}(10^{-3})$. This makes it another appealing place to search for new physics, which could manifest itself through relatively large values of CP asymmetry. The asymmetry can be separated into three pieces:

$$A_{CP}(D \rightarrow f) = \frac{\Gamma(D \rightarrow f) - \Gamma(\overline{D} \rightarrow \overline{f})}{\Gamma(D \rightarrow f) + \Gamma(\overline{D} \rightarrow \overline{f})} = a_f^m + a_f^d + a_f^i.$$

The first contribution to the asymmetry, a_f^m , is that of mixing, and is nonzero when the mixing parameter $p \neq q$, as described previously. The second contribution, a_f^d , is a direct component, where the decay amplitudes of D and \overline{D} to final states f and \overline{f} are unequal. The last contribution, a_f^i , comes from interference between the mixing induced and direct CP violation. This contribution is usually represented as an angle ϕ , defined as:

$$\phi = \arg \frac{q\mathcal{A}(\overline{D} \rightarrow \overline{f})}{p\mathcal{A}(D \rightarrow f)}.$$

Searches for CP violation can thus be conducted in both time-dependent mixing measurements as well as time-integrated measurements of direct CP asymmetries. Both types of measurements are well-suited to e^+e^- environments.

3 D meson production and measurement

At the B factories, charm mesons are copiously produced as part of the continuum process $e^+e^- \rightarrow c\overline{c}$. A typical experimental technique to identify neutral D mesons is to use the decay process $D^{*\pm} \rightarrow \pi_s^\pm D^0$, where π_s^\pm is a characteristic “slow” pion. By measuring the slow pion charge, the flavor of the neutral D meson is identified. The decay length of the D^0 can be measured with a vertex fit to the D^0 decay products, and the decay length can thus be inferred as the distance from the decay vertex to the interaction region. Decay time distributions and asymmetries can thus be measured for a wide variety of states.

While it is true that similar measurements can be made at hadron collider experiments, such as those at the LHC, the e^+e^- environment is significantly cleaner. This is more suitable for final states that include neutral particles (e.g., π^0 or η). Furthermore, since the full center-of-mass energy of each event is also known, remaining particles not associated with the signal $D^* \rightarrow D \rightarrow f$ decay can be reconstructed as part of a tag meson, D_{tag} . In this way, it is possible to identify signal decay chains with missing energy.

Since the B factories usually operate at or above the $B\overline{B}$ threshold, there is a potential background from D^* mesons produced from B meson decays. However, these backgrounds are kinematically well separated from continuum D^* mesons, and do not significantly impact the analysis once D^* momentum criteria are imposed.

4 Belle II at SuperKEKB

The KEKB B factory began physics operation in 1999. In over a decade of running, KEKB delivered a peak luminosity of $2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a total integrated luminosity of over 1 ab^{-1} , allowing the Belle detector to accumulate a large experimental data set, primarily at the energy of the $\Upsilon(4S)$ resonance.

In 2010, KEKB ceased operation to begin upgrading to SuperKEKB, which is expected to provide the upgraded Belle II detector with more than 50 ab^{-1} by 2022. Details on both the SuperKEKB and Belle II upgrades can be found elsewhere [1], but two specific system upgrades are briefly described, as they are particularly relevant to charm studies.

Precision tracking at Belle was provided by a silicon vertex detector (SVD), consisting of four layers of double sided silicon strip detectors [2]. At Belle II, this system will be replaced with two layers of DEPFET pixel detector, surrounded by a four layer SVD. The inner radius of the precision tracker thus decreases from 20 mm to 13 mm, while the outer radius increases from 8.8 cm to 13.5 cm. The improved resolution of the pixels and the overall increase in coverage and acceptance correspond to an expected $\sim 25\%$ improvement in vertex resolution and $\sim 30\%$ gain in efficiency to reconstruct the displaced vertex of $K_S^0 \rightarrow \pi^+\pi^-$.

Belle II also benefits from significant upgrades in particle identification (PID) capabilities. Belle utilized threshold aerogel Cherenkov detectors and time-of-flight counters as dedicated PID devices. Belle II replaces these systems with two ring imaging Cherenkov devices: a time-of-propagation detector in the barrel, and an aerogel RICH in the forward endcap. The significant improvements in $K\pi$ separation reduce kinematic reflections. For example, the mode $D^0 \rightarrow \pi^-\pi^+\pi^0$ suffers some background from $D^0 \rightarrow K^-\pi^+\pi^0$ when the kaon is misidentified as a pion. The improved particle identification at Belle II should help to reduce uncertainties due to these effects.

5 Mixing and Mixing-Induced CP Violation

Measurements of $D^0\overline{D}^0$ mixing have been performed in a variety of final states, with evidence for mixing observed by Belle, BaBar, and CDF. While the mixing parameters of ultimate interest are the x and y defined previously, each final state allows access to these parameters in different combinations. Some modes, such as $D^0 \rightarrow K_S^0\pi^+\pi^-$, allow direct access to x , y , $|q/p|$, and ϕ . In many cases, the observables are combinations of these underlying parameters. For example, the modes $D^0 \rightarrow K^+K^-$ and

$D^0 \rightarrow \pi^+\pi^-$ allow measurement of y_{CP} and A_Γ , which are defined as:

$$y_{CP} = y \cos(\phi) - \frac{1}{2}A_M x \sin \phi$$

$$A_\Gamma = \frac{1}{2}A_M y \cos \phi - x \sin \phi,$$

with A_M defined as

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}.$$

Thus, in order to fully utilize the existing experimental data, information from all modes is combined into a global fit for x , y , $\arg(q/p)$, and $|q/p|$ [3]. The current global fit to these values is shown in Figure 1. The fitted parameters and their uncertainties are:

$$x = (0.63 \pm 0.19)\%$$

$$y = (0.75 \pm 0.12)\%$$

$$|q/p| = (0.88 \pm 0.17)$$

$$\phi = (-10.3 \pm 9.2)^\circ.$$

While the no-mixing hypothesis is excluded at high statistical significance ($> 10\sigma$), the observed levels of mixing are compatible with Standard Model expectations. The global fit remains compatible with the hypothesis of no CP violation.

The strength of the Belle II charm physics program lies in its ability to access many final states in the same experiment. This ensemble of data allows for precision determinations of the mixing and CP violating parameters. To see the expected effect of Belle II measurements, a similar global fit is performed using projected sensitivities at 50 ab^{-1} of integrated luminosity for the following modes: K^+K^- , $\pi^+\pi^-$, $K^+\pi^-$, and $K_S^0\pi^+\pi^-$. The expected uncertainties for these measurements are shown in Table 1. In estimating these sensitivities, anticipated improvements from statistics are included, as well as improvements to systematic uncertainties that are expected to decrease with higher statistics.

Projected results from these modes are combined into a global fit, with results shown in Figure 2 and Table 2. These and other Belle II sensitivity projections can be found in Ref. [4]. Note that these results do not take into account all possible decay modes, or include contributions from other experiments. Even with these conservative sensitivities, the improvements are dramatic. Sensitivity to both mixing and CP violation parameters is expected to improve considerably.

These types of measurements of mixing and CP violation parameters provide powerful constraints on many scenarios involving new physics. For example, Reference [5] utilizes the wide array of available D mixing measurements to set constraints on models with a fourth generation of fermions, extra gauge bosons, extra dimensions, and

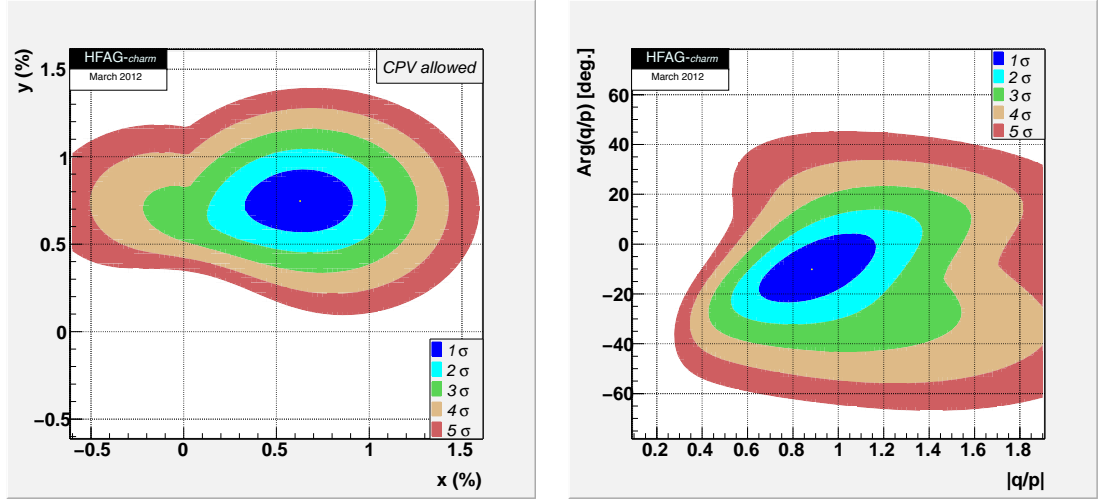


Figure 1: (Left) Results of the current global fit to charm mixing parameters, allowing for CP violation. The origin corresponds to the no-mixing point. (Right) Global fits to the current CP violation parameters. The no-CP violation point corresponds to the point (1,0). Both plots are from Reference [3].

D^0 Decay Mode	Observable	Uncertainty (%)	
		Current ($\sim 1.5 \text{ ab}^{-1}$)	Belle II (50 ab^{-1})
$K_S^0 \pi^+ \pi^-$	x	0.211	0.10
	y	0.186	0.08
	$ q/p $	32	9
	ϕ	0.32 rad	0.07 rad
$\pi^+ \pi^- / K^+ K^-$	y_{CP}	0.217	0.05
	A_Γ	0.248	0.03
	A_{CP}	0.240	0.07
$K^+ \pi^-$	x'^2	0.0195	0.009
	y'	0.321	0.16
	A_D	3.5	1.7
	R_D	0.013	0.0015

Table 1: Projected Belle II sensitivities, relative to existing world averages, for mixing and mixing-induced CP violation parameters in selected D^0 decay modes.

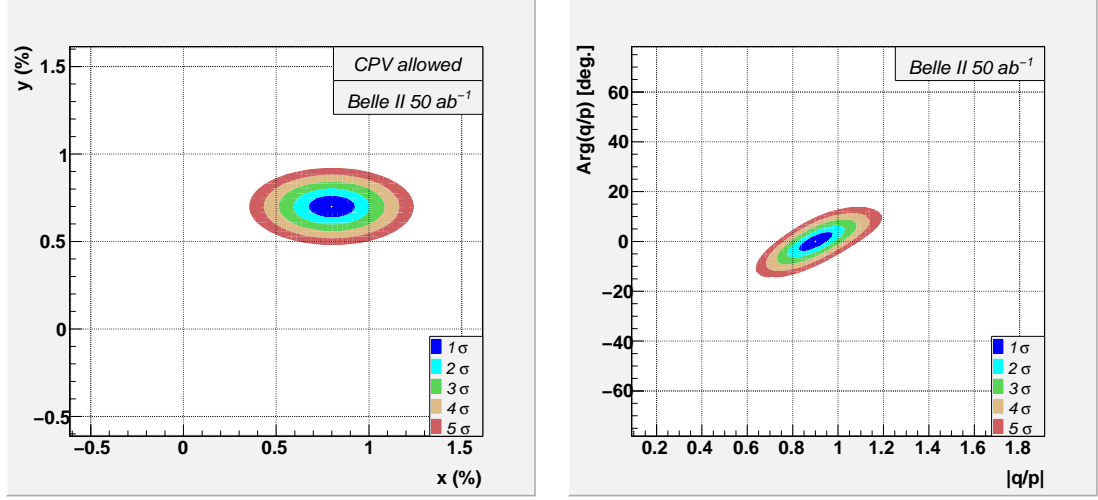


Figure 2: Equivalent fits to Figure 1, but using only Belle II projected uncertainties for the D decay modes included in Table 1.

Parameter	Result of current global fit	Expected Belle II precision
x	$(0.63^{+0.19}_{-0.20})\%$	$\pm 0.08\%$
y	$(0.75 \pm 0.12)\%$	$\pm 0.04\%$
$ q/p $	$0.88^{+0.18}_{-0.16}$	± 0.05
ϕ	$(-10.1^{+9.5}_{-8.9})^\circ$	$\pm 2.6^\circ$

Table 2: Projected sensitivities to selected neutral D meson mixing and CP violation parameters, relative to results of the existing global fit.

many others. Thus, even if a "smoking gun" signal of large mixing-induced CP violation is not observed at Belle II, the improvements to the ensemble of all D mixing measurements will help to squeeze the parameter space of an extremely varied set of new physics models.

6 Time-integrated searches for CP violation

In addition to the mixing-induced CP violation searches previously described, it is also possible to search for direct CP violation using time-integrated measurements. The observable for direct CP violation searches is an asymmetry in the decay widths of a decay mode and its charge conjugate:

$$A_{CP} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}.$$

As with mixing and indirect CP violation, the expected level of A_{CP} in the Standard Model is small, so observation of large direct CP asymmetry in D decays could be indicative of new physics.

Measurement of A_{CP} can be contaminated by environmental effects. Reconstruction asymmetries between positive and negative kaons or pions must be estimated and removed from the raw measurement. Furthermore, the underlying production process may have an intrinsic asymmetry. At Belle and Belle II, for example, there is a forward-backward asymmetry from interference between γ and Z production channels. This contribution must be corrected out to determine the contribution from D decays.

At the LHC, the underlying pp initial state is not CP symmetric, making absolute measurements of direct CP asymmetries prone to systematic uncertainties. However, these large uncertainties can cancel out if the difference in asymmetry between two modes is measured. LHCb has reported a difference in direct CP asymmetry between the final states K^+K^- and $\pi^+\pi^-$ [6]. Their result is $\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\%$, with a significance of 3.5σ . This constitutes the first evidence for direct CP violation in the D meson system. CDF has also confirmed this result with their own measurement, $\Delta A_{CP} = [-0.62 \pm 0.21(\text{stat.}) \pm 0.10(\text{syst.})]\%$, with a significance of 2.7σ [7].

It is not yet clear if the LHCb result is consistent with the Standard Model. For example, some calculations indicate that Standard Model penguin amplitude contributions to these processes may account for the result, and that the key to unraveling this contribution is to measure A_{CP} in a variety of modes [8]. Given the measured value of ΔA_{CP} between the K^+K^- and $\pi^+\pi^-$ modes, the authors of Ref. [8] predict non-zero CP asymmetries in the following decays: $D^+ \rightarrow K^+\bar{K}^0$, $D^0 \rightarrow \pi^0\pi^0$, $D_s^+ \rightarrow \pi^+K^0$, and $D_s^+ \rightarrow \pi^0K^+$. They also predict null asymmetries for

Decay Mode	$\mathcal{L}[\text{fb}^{-1}]$	$A_{CP} (\%)$	
		Belle	Belle II (50 ab^{-1})
$D^0 \rightarrow K_S^0 \pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	± 0.05
$D^0 \rightarrow K_S^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.10
$D^0 \rightarrow K_S^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.10
$D^0 \rightarrow \pi^+ \pi^-$	540	$+0.43 \pm 0.52 \pm 0.12$	± 0.07
$D^0 \rightarrow K^+ K^-$	540	$-0.43 \pm 0.30 \pm 0.11$	± 0.05
$D^0 \rightarrow \pi^+ \pi^- \pi^0$	532	$+0.43 \pm 1.30$	
$D^0 \rightarrow K^+ \pi^- \pi^0$	281	-0.6 ± 5.3	
$D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$	281	-1.8 ± 4.4	
$D^+ \rightarrow \phi \pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.05
$D^+ \rightarrow \eta \pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.20
$D^+ \rightarrow \eta' \pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.20
$D^+ \rightarrow K_S^0 \pi^+$	673	$-0.71 \pm 0.19 \pm 0.20$	± 0.05
$D^+ \rightarrow K_S^0 K^+$	673	$-0.16 \pm 0.58 \pm 0.25$	± 0.10
$D_s^+ \rightarrow K_S^0 \pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.30
$D_s^+ \rightarrow K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.10

Table 3: Projected Belle II sensitivities, relative to existing Belle measurements, for direct CP asymmetries in selected D and D_s decay modes. When two uncertainties are given separately, they are statistical and systematic. Otherwise, the uncertainty is a combined uncertainty. Modes without a Belle II sensitivity can be studied at Belle II, but detailed sensitivity studies have not been conducted at this time.

$D^+ \rightarrow \pi^+ \pi^0$ and $D^0 \rightarrow K^0 \overline{K}^0$. It is again clear that to make significant headway in our understanding of possible new physics in this sector, measurements of CP asymmetries for as many modes as possible are required.

Belle II is well situated to make many of these measurements, and can make uniquely useful contributions to modes with neutral particles in the final state, complementary to those states accessible at LHCb. A list of selected Belle measurements and prospects for improved measurements at Belle II is given in Table 3. As with the previously described projections, the Belle II values incorporate improvements due to statistics as well as those systematic errors that are expected to improve with statistics. As these further measurements become available, the necessity of new physics to explain direct CP asymmetries of D meson decays may be revealed.

7 Conclusions

Upgrades at Belle II and SuperKEKB are now underway, with physics operation planned to begin in 2016, and a dataset of 50 ab^{-1} expected by 2022. This large data sample will include more than 6×10^{10} charm events, allowing excellent sensitivity to many D meson mixing and CP violation parameters. In addition to the obvious benefits afforded by a factor of 50 increase in statistics, a key element of the Belle II charm program is its large breadth. Furthermore, many of the modes accessible at Belle II, such as decays with neutral final state particles or missing energy, are challenging or impossible in a hadron collider environment. Thus, the Belle II program is nicely complementary to those underway at the LHC. Since mixing parameters and CP violation studies, both indirect and direct, require a large number of modes to make definitive conclusions about whether new physics is present, this complementarity of Belle II measurements and others will be a key element in advancing these searches for new physics.

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